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THE HAZARD OF AN EXPLOSION OF THE ARIANE 5 LAUNCHER-THE RISKS FOR THE ASTRONAUTS SITTING ON THE EJECTOR SEATS

BY

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Abstract

Europeans will soon send inhabited missions into space with the Ariane 5 launcher and spaceshuttle Hermes combination. In case of an incident at launch, either on the pad or up to some speed after launch, it is proposed to eject the flight crew to safety on individual ejector seats. The risks which would be confronted by the astronauts have been studied.

This paper presents the development of a method for calculating the probability that a fragment of the launcher

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1

hits an ejector seat either in flight or at ground level during the initial launch phase.

Introduction.

Despite a high confidence in the launcher's reliability, the risk of accidents exists ; the possibility of explosion of the launcher is not to be excluded.

With the projected inhabited missions of Ariane 5, ejection of the astronauts on individual ejector seats is proposed when its explosion risk has been «estimated» as excessive.

If the seats have been ejected succesfully, accurate evaluation of the hazards is important to assure the safety of the astronauts after the explosion. These Hazards are known and are :

- the shock wave propagating through the air (gas dynamic problem...),
- thermal phenomenon due to the fireball (thermal exchanges, combustion, chemical kinetic problems...)
- fragment trajectories.

The last item is considered a danger due to the risk of launcher fragments hitting the astronauts on the ejector seats and is also the subject of this paper..

It is interesting to calculate whether there exists an «optimal» time, beyond which the hit probability is less than a given value.

Presented in the following is the current stage of our work in trying to solve this problem.

Ejection of the astronauts.

In all ejection situations, the mode of operation of the seat is the same. As the seat separates from the Hermes cabin, the drogue is deployed (the deployment can be delayed for ground level escape) and maintains the seats attitude during rocket burn. The parachute deployment phase will follow a

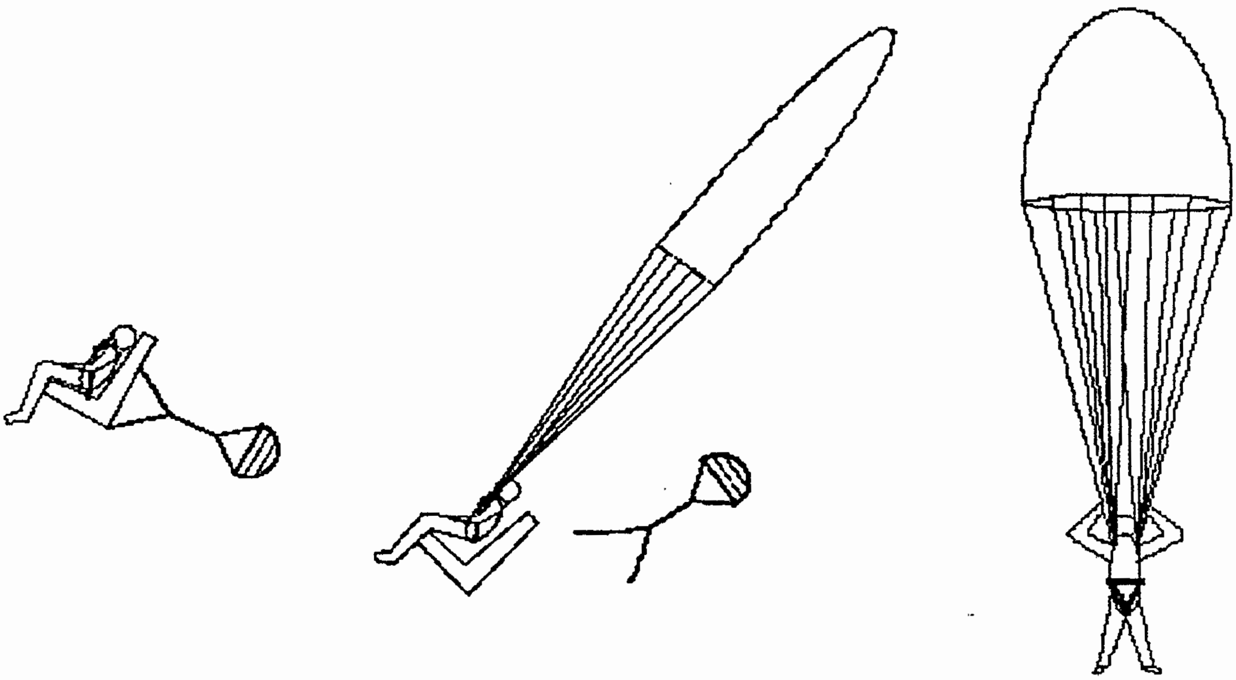

Fig. 1 - ejector seat sequence

conventional ejector seat sequence . Finally, the crewperson is pulled off the seat by the inflating parachute and descends with it.

Description of the Ariane 5 Launcher.

In its «HERMES» configuration, Ariane 5 consists of a cryogenic stage H155 (155 tonnes of liquid oxygen and liquid hydrogen) propulsed by a HM60 Vulcain motor and two boosters with solid propellant P230 (230 tonnes of Ammonium Perchlorate).

Elements of the problem.

Accidents involving liquid propellant rockets have shown that they can generate violent explosions. We know however that while their potential explosive yield is very high, their actual yield is in fact

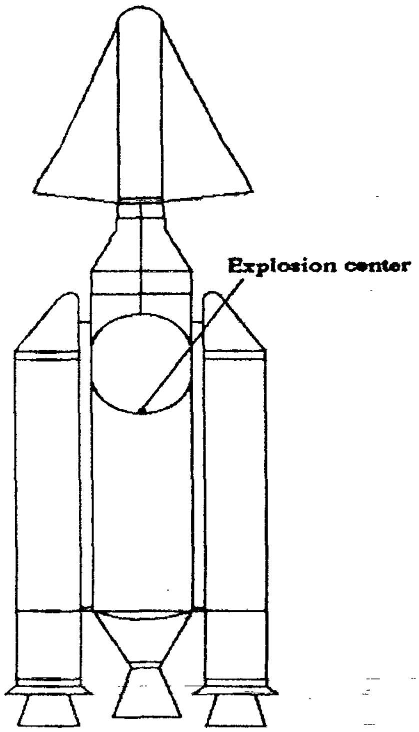

Fig 2 - Ariane 5 launcher

much lower.

The most likely causes of accidents are :

- failure of an interior bulkhead which separates fuel and oxidizer within the stage,
- excessive air-load on, and break-up of the launcher (malfunctioning of the vehicule...)
- destruct command (the launcher could be considered dangerous to the population...)
- others...

Before proceeding to the description of the model, we must specify that our approach is of the first order. That is to say that we only treat amongst the accident scenarios those which will give the greatest explosion energy.

-A- Description of the model - The Launcher explosion - First model.

As described in [1,2], because the Liquid Oxygen/Liquid Hydrogen mixture is not hypergolic, mixing between these products can occur before explosion. As mentioned earlier, we will overestimate the reaction energy, so the T.N.T. equivalent «Y» is taken to be the upper bound as described in [1]. In fact we have a relation as :

$$Y = Y(W_p)$$

where W_p is the total propellant mass prior the explosion. With Y we may deduce the effective

reacting propellant mass W_R which has volume V_R and released energy E ([1]).
Classically, if we compare this explosion with a mechanical one (compressed gas reservoir), we

$$E = \frac{P \ V_R}{\Gamma - 1}$$

obtain the «pressure» P of the combustion gases by manipulating the relation :

where Γ is a generalized local adiabatic exponent.
Alternatively, we know that detonation (Chapman-Jouguet detonation) can occur after the ignition. Use of a code modelling thermochemical relations shows that the characteristics of the C-J detonation products for a stoechiometric mixture are :

-the products : H2O, O2, H2, OH, H, O.
- detonation temperature : 4347 K.
- C-J pressure : 43770 Bars.

If, as a first approach, we suppose that the pressure, specific volume, temperature... profiles after the detonation shock are of the Taylor-Zeldovich type for a spherical propagation, we have the alternative initial condition for the gas pressure.

Calculation of the fragment velocities (a first approach).
In a first step, we «construct» the launcher. A launcher is composed of structures (propellant reservoirs for example...), of objects (cryogenic motors, Helium sphere...) and propellant. The explosion center may then be placed.
The ejection speed of a given fragment is assumed to be consistent with that of a «cone element» C_Ω , i.e. a cone defined by a solid angle Ω emanating from the explosion center. The structures and the unburnt propellant included in the cone C_Ω are all part of the fragments' «environment» (Fig. 3). Its mass W_T is concentrated on the surface of a thin spherical cap. A technique following that of Bessey's

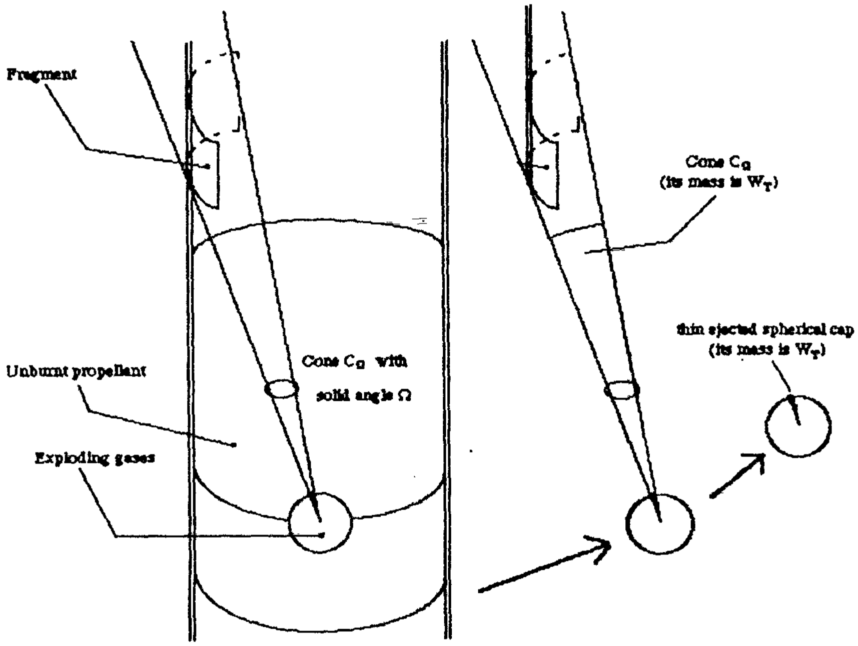

Fig. 3 - «cone element» C_Ω

([4]) may be used with a correct state equation ([27,45]) for the exploding gases to calculate the fragment velocities.

Calculation of the fragment velocities (a second approach).

Another method to compute (estimate) the ejection speed of a given fragment is to study the interaction between fluid and rigid moving bodies ([41,42]). In this case, we utilise the idealized cone environment described in the former paragraph.

The two-dimensional domain is discretized, and an algorithm for the advancement in time of the solution can be applied as follows :

-1- the Euler partial differential equations are solved (finite differences) ; the «fragment» (with the mass W_T) is considered as a reflector,

-2- we compute the body forces from the pressure field (no body moments),

-3- we compute the acceleration of the fragment, and we move it by one time-step,

-4- the grid is adapted,

-5- we update the characteristics of the gas around the fragment,

-6- back to -1-

Comparing the results between the above two methods, we have observed that the velocities are greater using the former method (up to 100% greater for small values of Ω [13]). Eventhough the former method gives seemingly erroneous results, similar results to the second method may be achieved by application of a modified discharge coefficient k. The former method then is quite useful as it is quicker than the latter at estimating the initial velocities and may be easily corrected.

Breakup of the booster P230.

We must consider a simultaneous explosion of the H155 and the two P230 ; the booster fragment velocities can be estimated following the same procedures outlined above.

Fragment trajectories.

These are calculated using the fourth order Runge-Kutta method. The drag coefficient of a fragment

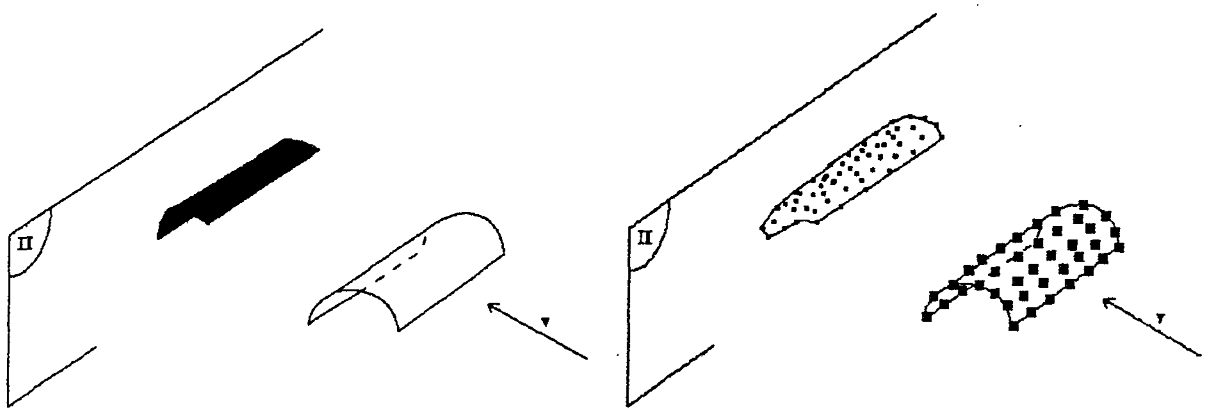

Fig 4 - Calculation of A_{MAX} and A_{AVG}

is a function of the two dimensionless parameters $A_R = A_{MAX}/A_{AVG}$ and Mach number ([43]). A_{MAX} and A_{AVG} are the maximum and average presented fragment areas. We suppose there is no lift, and the wind is a function of altitude (z) but there is no z component.
We can estimate A_{MAX} and A_{AVG} in the following way. If these two values are not «evident», we «discretize» the fragment (Fig. 4), then we project these points on to a plane. A_{MAX} is the greatest area of the smallest polygon containing all the projected points when the projection direction is varying; A_{AVG} is the average value.

-B- Description of the model - The Launcher explosion - second model.

Computational time in the first model is very important for fragment treatment. Replacing every costly (computational time) step in the first approach by an analytic (or quasi-analytic) formula reduces calculation time drastically.

Fragment velocities - Analytic formulation.

By studying the physical parameters needed in the iterative calculation of a fragment's velocity V,

$$V = V\left(\Omega, \frac{W_T}{W_\Omega}\right)$$

it can be shown (with realistic simplifications and similitude theory) that V can be written :
W_T is the total mass ejected in the cone C_Ω with solid angle Ω, W_Ω is the compressed combustion gas mass in C_Ω. The above function V(.,.) is determined by parameter estimation with the simplest suitable functions bases [8]. The parameter estimations may easily be computed using a computational system such as us «Mathematica». The result of this analytic approach compares well with the former computational algorithm ([8]).

Fragments trajectories - quasi analytic formulation [36].

The position and the velocity of the fragment must be determined on several points along the trajectory; we need intermediary results.

Before proceeding to the description of the problem's solution it is necessary to define the approximated physical environment :

- assume non-sphericity of the Earth for the impact point calculation,
- include effects of the Earth's rotation,
- the Earth's gravitational acceleration (g) varies with altitude,
- atmospheric effects; in this first study, in order to develop a method able to give results in real time, we considered drag effects only (atmospheric density and fragment drag coefficient are assumed to vary as a function of position). We assume that the effect of lift is averaged out by the fragments tumbling motion and there is no wind.

The results' accuracy must be consistent with the uncertainties related to the physical parameters:

- uncertainty in the main body state vector (i.e. position and velocity) at vehicle destruct time,
- uncertainty in destruct velocity imparted to the fragment,
- uncertainty due to effects of the atmosphere during freefall.

Our methodology is to solve the problem utilising a quasi-analytic approach. It's not possible to solve the complete governing equations of the system analytically, some approximations to these complete equations must be applied to determine achievable analytic solutions.

This is done by applying a uniform space partitioning technique. In each sub-space created we can simplify the physical framework and thus solve analytically the reduced equations. The new simplified theoretical framework within each sub-space becomes:

- plane movement,
- drag coefficient and atmospheric density are assumed to be constant,
- drag force direction is assumed to be constant,
- Earth's gravity is assumed to be constant.

Such a partitioning is defined by the triplet (dx, dz, da) where:

- dx is the length (overall free-fall range) of the sub-space,
- dz is the height (maximum altitude variation) of the sub-space,
- da is the maximum variation of the fragment velocity angle inside the sub-space.

Thus, the fragment impact point calculation consists of partitioning and making a sequence of elementary calculations inside each subsequent sub-space. The results of the calculations within each sub-space become the initial conditions of the next, with the constant parameters updated.
The final result accuracy is improved albeit at the expense of calculation time by finer partitioning. The choice of triplet (dx, dz, da) influences our method's operation and is a way to control response time or result accuracy.
In order to improve the method's performance, atmospheric effects beyond a certain altitude may be eliminated as air density reduces, as a result an analytic calculation taking only gravitational forces into account is performed.

The method has been tested for a wide range of realistic trajectories and comparison has been made with reference trajectories calculated by numerical integration. The computational time remains low even for accurate results i.e. in the case where the calculation error is of the same order as those due to the atmospheric parameter uncertainties (i.e. drag coefficients, atmospheric density, ...). The computational time can be up to 1000 times less than that of numerical integration; the average gain is usually of the order of 100 times.
To give an idea of the dimensions involved, the triplet for a partition could be : dx = 50 km, dz = 1 km, da = 1 .

The main advantage of this method is that its control mode (dx, dz, da) can be chosen independently of the initial conditions. Computation time is only dependent on desired accuracy (i.e. chosen triplet) and not on the initial conditions. These characteristics are particularly useful for real time applications.

-C- Hit probability of the seats.

The above model is deterministic ; however some parameters are «uncertain». To account for this, we have created a model which utilises the Monte-Carlo method. The values for certain variables are

randomly selected for each fragment within «uncertain bounds». These are :

- Initial fragment velocity, because of the uncertainty of the propellant weight inside the cone C_n,
- The attitude of the fragment,
- Drag coefficient ([43]).

Computation of hit probability is simple and classical ; if necessary, the trajectories of the fragments or the seats are approximated by cubic polynomials. Attitude, «configuration» (propulsed or with a parachute) of the seats and relative movement with the fragments are taking into account.

The fragmentation.

An important parameter in a Monte-Carlo approach is the number of hazardeous fragments, their mass distribution and their location on the launcher.

At the moment, this is for us an unresolved problem.

We know that the number of fragments over a given mass may be predicted by a Mott equation ([2]) from which we have simply extrapolated for the Ariane 5 launcher.

Future work.

An obvious extension of our quasi-analytic trajectory calculation method will be to take into account lift and wind effects.

For the Monte-Carlo modeling, an obvious extension is the random choice of the T.N.T. equivalent parameter «Y», including multiple explosions, different explosion scenarios..., and an improved knowledge of the corresponding fragmentation.

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11

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